Experimental study on the biaxial bending cyclic behaviour of RC columns

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ABSTRACT:
The available experimental studies on the inelastic 3D response of axially loaded members under biaxial bending moment loading histories are limited. Possibly, this is partially due to the uncertainty of combining bending moment's histories in the two orthogonal directions that adds considerable complication to the problem.
Three types of cantilever reinforced concrete columns with constant axial load were subjected to cyclic uniaxial and biaxial tests. It was intended to gain enhanced knowledge concerning the behaviour or RC columns that allows for the calibration of simplified non-linear models. The experimental campaign is described, test results are presented and discussed comparing the uniaxial and the biaxial tests and the effect of the different biaxial load paths in the columns behaviour.

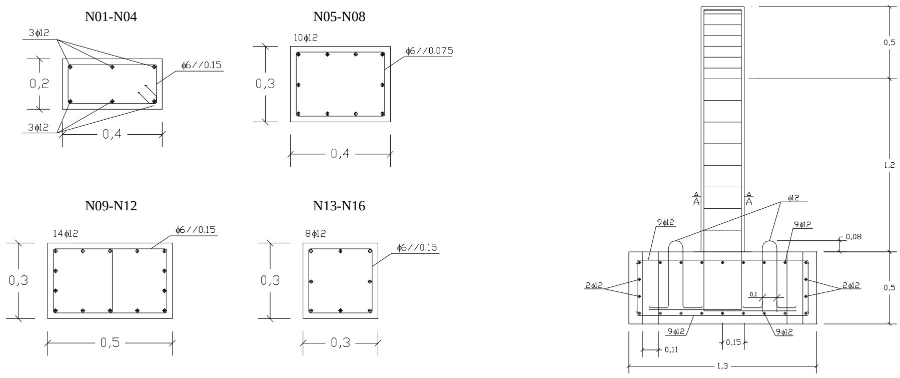
Keywords: RC columns, biaxial cyclic behaviour, experimental study

1. BACKGROUND AND OBJECTIVES

The response of reinforced concrete (RC) members subjected to axial load in conjunction with biaxial bending moment reversals is recognized an important research topic for building structures in earthquake prone regions. On one hand, the response of RC building columns to earthquake actions deals in general with its three-dimensional (3D) response, due to the randomly characteristics of the earthquakes direction, and to the building irregularities itself. On the other hand, the 2D features of bending moment histories applied to a given RC column section tends to reduce its actual capacity and to accelerate the strength and stiffness deterioration process during successive load reversals. Experimental research work on the inelastic response of RC members under compression axial force and biaxial lateral cyclic bending loading conditions is currently very limited. Uncertainties concerning the relation and combination of the two orthogonal horizontal loading paths, associated to the complexity of the experimental setup, certainly, justify this lacuna. As a consequence, nowadays the current knowledge on the inelastic response of RC columns under biaxial cyclic moments is very much behind our understanding of the behaviour under 1D cyclic bending with compression axial load [1-3]. As stated before, the available test results for biaxial bending under constant axial load are not so extensive when compared to those on 1D bending, although they have been delivered over a period of almost 30 years. Contributions can be found for instance from Takizawa and Aoyama, 1976 [4]; Otani et al., 1980 [5]; [6]; Bousias et al., 1992 [7]; Kim and Lee (2000) [8]; Qiu et al., 2002 [9], Tsuno and Park, 2004 [10], Nishida and Unjoh, 2004 [11], Umemura and Ichinose, 2004 [12], Kawashima et al., 2006 [13], Li et al., 2008 [14], Acun, 2010 [15] and Shuenn-Yih Chang, 2010 [16].

2. COLUMN SPECIMENS' DESCRIPTION, TESTING SET-UP AND LOADING SCHEME

The current experimental work is part of a large testing campaign promoted by the Laboratory of Earthquake and Structural Engineering (LESE), of the Faculty of Engineering of Porto University (FEUP), for the study of RC columns (of buildings and bridges) under horizontal cyclic loadings [17, 18]. The main purpose of this experimental work is to study the cyclic behaviour of rectangular RC columns, under biaxial horizontal cyclic loadings. Four series of four rectangular type RC columns were constructed with different geometric characteristics and reinforcement detailing and cyclically tested for different loading histories. Two columns were tested under uniaxial loading (strong and weak directions) and two other under biaxial loading, all with constant axial force and subjected to displacement controlled conditions. The columns specimens are 1.70m high cast in a strong square concrete foundation block with 1.30x1.30m^2 in plan and 0.50m high. The section properties and the reinforcement steel detailing are presented in the Figure 1. Four holes are arranged at the foundation block to fix the specimen to the laboratory strong floor.



a) b)

Figure 1. RC column specimens' dimensions and reinforcement detailing: a) Cross-sections details, b) Specimen dimensions and general scheme of the reinforcement layout

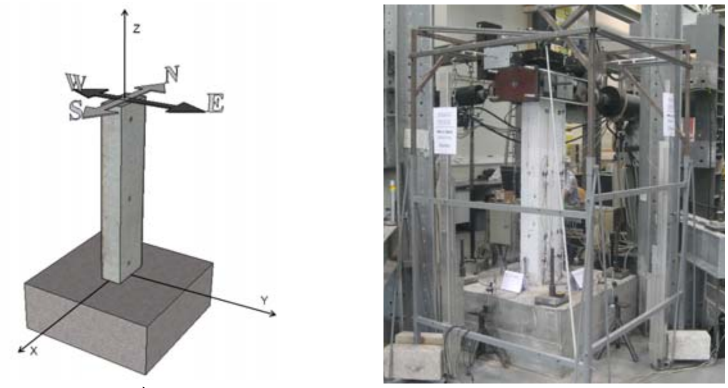
The materials considered for the specimen design phase were a regular concrete class C35/45 for columns N01-N04 and C30/35 for columns N05-N16, with reinforcing steel grade A400NR-SD. Tests on samples of the materials actually used in the construction (steel reinforcement and concrete) have been carried out. The average results for each series of columns are summarised in the Table 2.1 for the concrete according with the NP-EN 206-1. In what concerns the results the concrete, the first series (Columns N01-N04) have confirmed the expected results, i.e. a good concrete according with the expected value. The results for the concrete cylindrical specimens for the second, third and fourth column series (columns N05-N016) have shown a poor quality concrete, with a mean compressive strength value bellow the expected one for the ordered concrete.

Figure 1 shows the setup adopted for the experimental testing campaign on RC columns. The system includes two independent horizontal actuators to apply the lateral loads on the column specimen, one with 500kN capacity and +/-150mm stroke and the other with 200kN capacity and +/-100mm stroke. A vertical 700kN capacity actuator was used to apply the axial load. Two steel reaction frames and a concrete reaction wall make the reaction system for the three actuators. The column specimens and the reaction frames were fixed to the laboratory strong floor with prestressed steel bars to avoid sliding and overturning of the specimen during testing, or sliding of the reaction frames. Since the axial load actuator remains in the same position during the test, while the column specimen laterally deflects, a sliding device (placed between the top-column and the actuator) is used in order to minimize spurious friction effects. For all the tested specimens, a constant axial force was imposed with the values listed in Table 2.1, concerning both absolute and normalized axial force.

In order to characterize the response of the column specimens, cyclic lateral displacements were imposed at the top of the column with smooth increasing demand levels. Three cycles were repeated for each lateral deformation demand level. This procedure allows understanding of the columns behaviour, the comparison between tests and the development and calibration of numerical models. The repetition of cycles for each displacement demand, allows capturing information to better understand the stiffness and strength degradation of the column, which is relevant also for the calibration of numerical models. The adopted load paths are summarized in Table 2.2 and the following nominal peak displacement levels (mm) were considered: 3, 5, 10, 4, 12, 15, 7, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80. For each column specimen, the test was stopped when the first steel bar fracture occurred.

Table 2.1. Axial force imposed and normalized axial stress

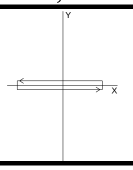
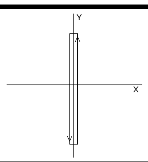
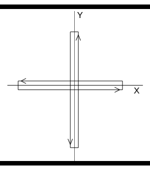
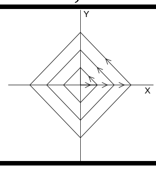
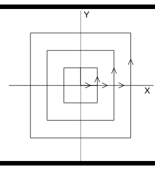
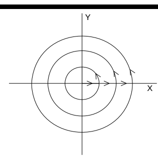
Column specimen	Axial force [kN]	Compressive ultimate strength (MPa)	$\nu = N/(A_c.f_c)$
N01-N04	170	48.35	0.04
N05-N08	300	21.40	0.12
N09-N12	300	24.39	0.08
N13-N16	210	21.70	0.10



a) b)

Figure 2. Testing setup: a) Scheme of the column specimens and testing directions; b) General view

Table 2.2. Loading paths

	N01, N05, N09, N13	N02. N06, N10	N03	N04, N07, N11, N14	N08, N12, N15	N16
Load path						

3. TEST RESULTS

3.1. Global results

The shear-drift curves obtained from the cyclic tests are shown in Figure 3 to 6. Figure 7 shows the results in terms of shear in X-direction *vs.* shear in Y-direction. From the analysis of the shear-drift curves remarkable differences can be found in the reloading stiffness for the uniaxial and biaxial test results. A clear pinching effect was observed for the rhombus load path, especially in the hysteretic curve for the column weak direction. The reloading stiffness for the quadrangular load path is larger than the one observed for uniaxial tests. Due to the fact that, for all the biaxial tests, the loading paths adopted in the experimental campaign start the first cycle (of each displacement level) always in the same direction (X, negative), a different response is obtained for those first cycles (comparing with the remaining ones). This effect is reduced in the subsequent cycles for the same displacement amplitude.

From the analysis of the measured horizontal load and displacement paths, it is observed a load path rotation when compared with the input displacement paths. This fact was already observed and reported in tests performed by other authors, as for example Takizawa and Aoyama [4], Otani [5] or Bousias *et al*. [7], referring a rotation in the range 10º-20º for square section columns. This rotation is a consequence of second order forces associated with the simultaneous imposition of zero displacement in one direction and a particular displacement value for the orthogonal direction. For the quadrangular paths, when the imposed displacement variation changes direction, i.e. after the path corner, the displacement imposed in the opposite direction is kept practically constant while a force reduction is observed in the latter direction in order to keep constant the corresponding displacement. This coupling effect results in a slight unloading, observed in the force-drift plots, contributing to an increase of the energy dissipation [1]. From the results for the square section columns tested under rhombus and quadrangular load paths, PB12-N14 and PB12-N15 specimens, respectively, it was observed that the path rotation is within the range reported by other authors. It was also further observed that such rotation depends on the section geometry. For the quadrangular load path this effect is more significant, wherein the rotation can reach 40º~50º in one direction and 3º~6º in the opposite one. For the rhombus load path the rotation observed was about 30º~35º in one direction and 7º~10º in the other direction.

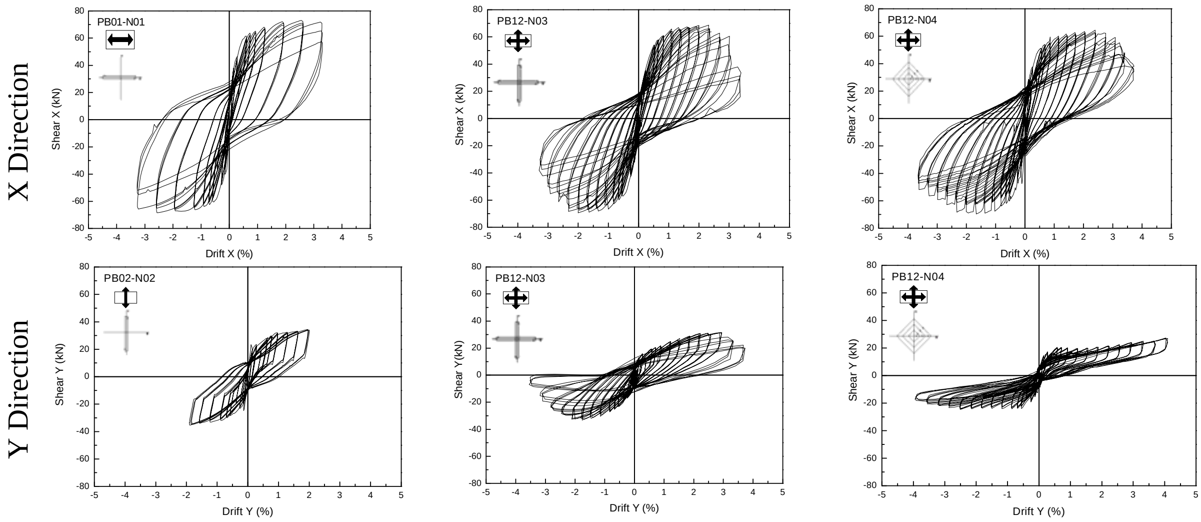


Figure 3. Shear-Drift hysteretic curves for columns N01 to N04

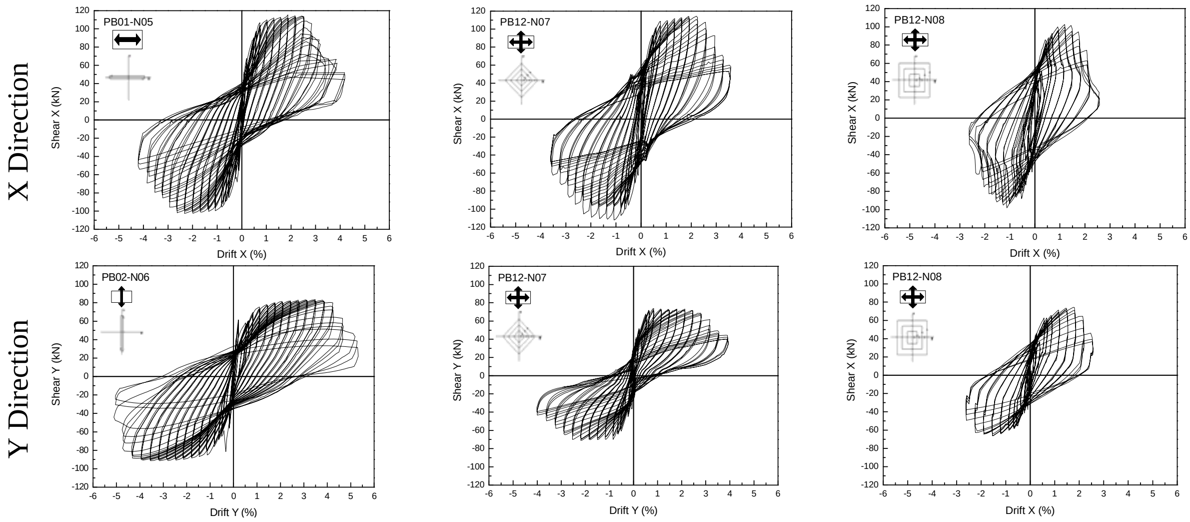


Figure 4. Shear-Drift hysteretic curves for columns N05 to N08

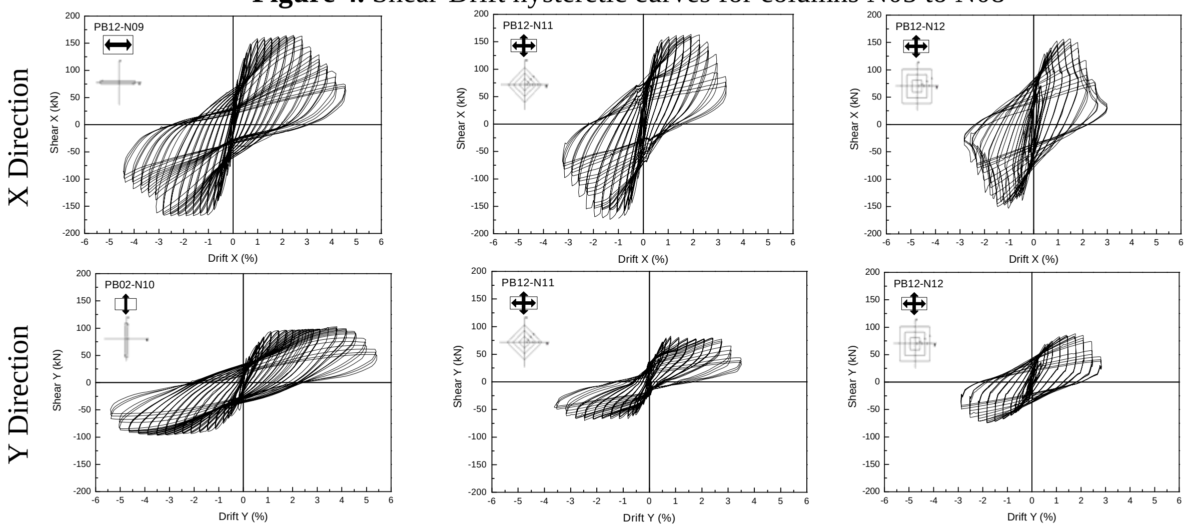


Figure 5. Shear-Drift hysteretic curves for columns N09 to N12

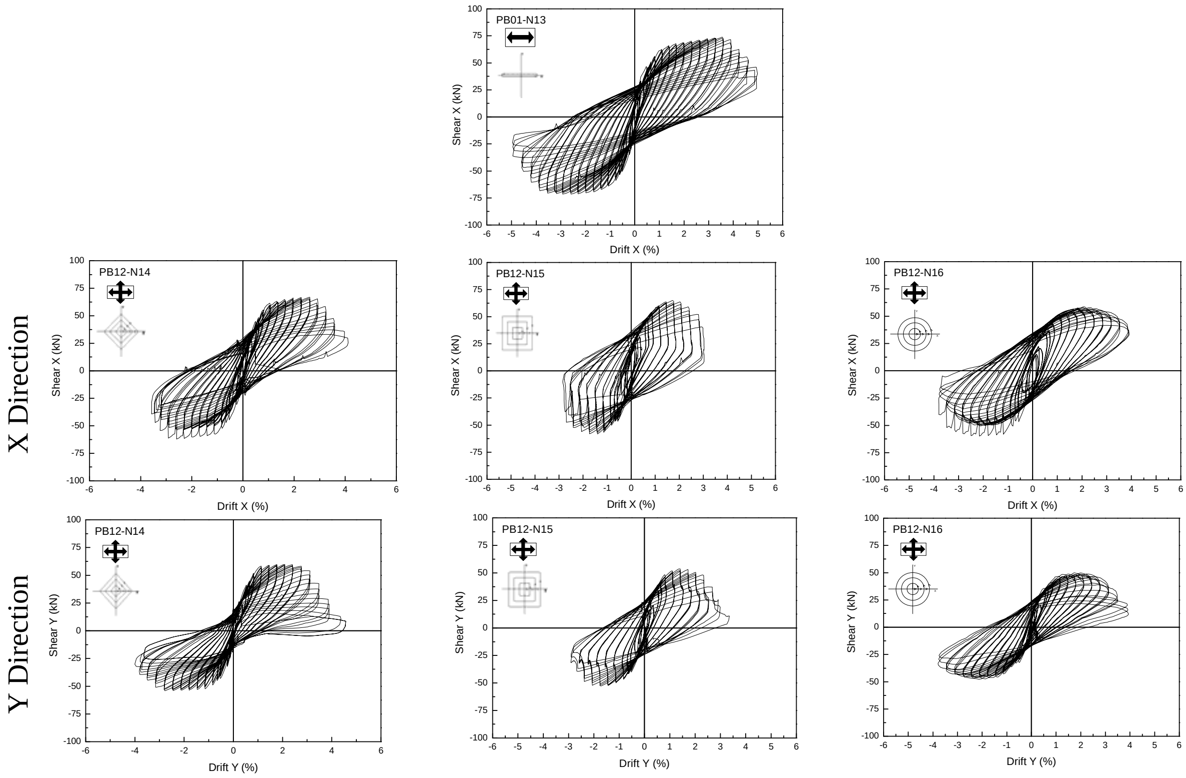


Figure 6. Shear-Drift hysteretic curves for columns N13 to N16

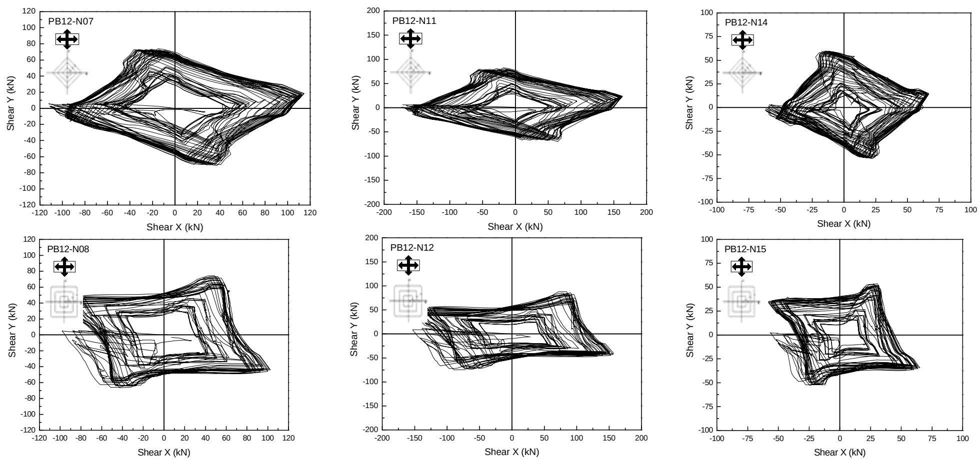
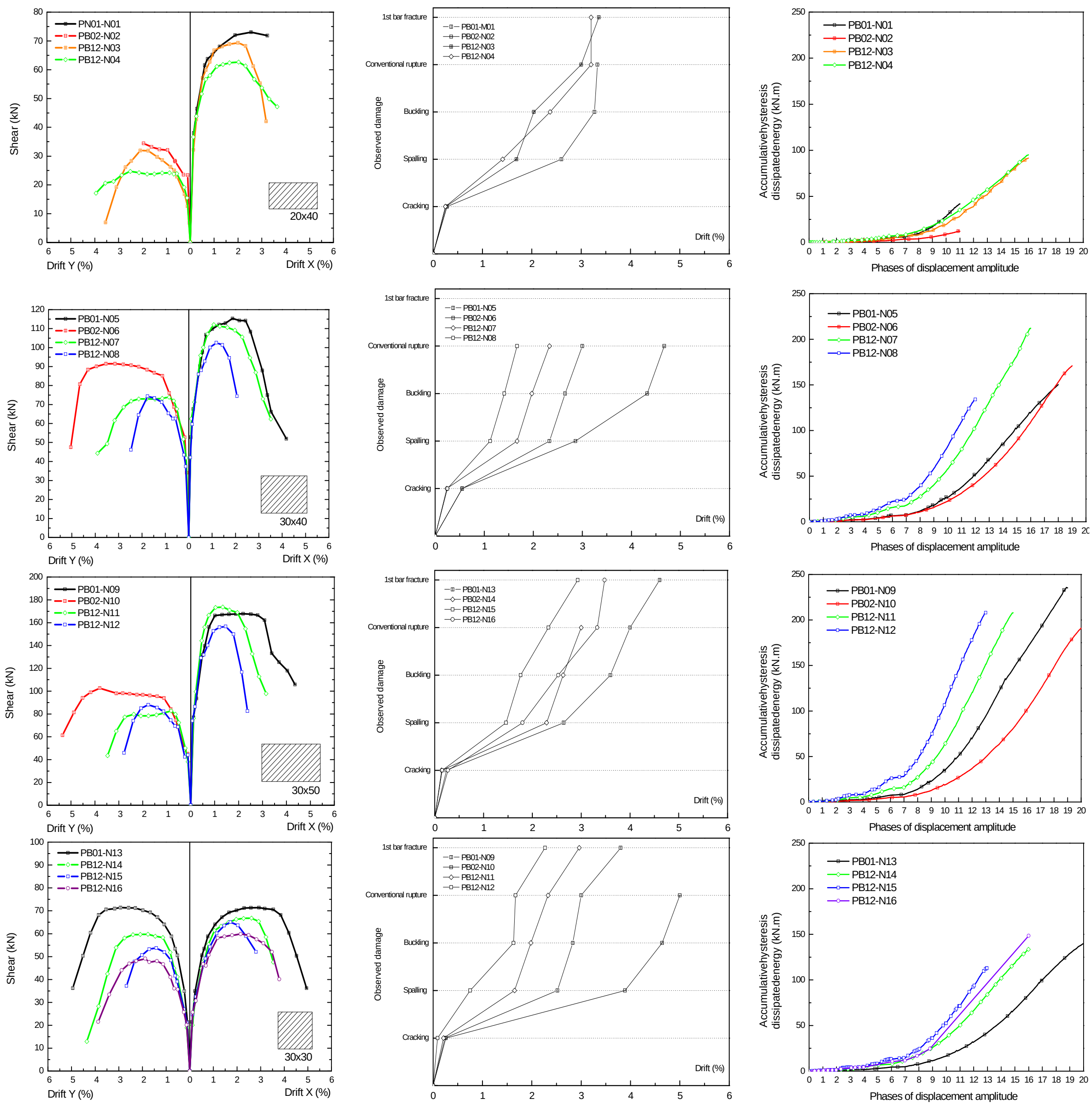


Figure 7. Shear in the X versus Shear in Y direction for columns tested with biaxial loading with rhombus and quadrangular load path

Further results concerning other response parameters, namely strength and stiffness degradation, energy dissipation and damage, are included in Figure 8 and discussed in the following sections.

3.2. Stiffness and strength degradation

The envelopes of the hysteresis curves for each tested column are plotted in Figure 8a, showing that the initial column stiffness is not significantly affected by the biaxial load path. Comparing the envelope shear-drift curves from uniaxial and biaxial loading tests, it is quite apparent the strength reduction with biaxial loading for both directions. This effect is more notorious in the columns' weak direction (Y direction). The maximum strength reduction due to the biaxial loading was observed for the columns tested with a quadrangular load path. For the cruciform load path imposed in column N03, the envelope curves obtained are similar to the obtained in the uniaxial tests.



a) b) c)

Figure 8. a) Force-drift envelopes for all column specimens and corresponding b) damage curves and c) cumulative hysteretic dissipation energy

3.3. Damage evolution

In order to understand the consequences of biaxial loading in the columns' damage, the comparison of drift values was made between different specimens corresponding to stages of concrete cracking, spalling, longitudinal reinforcement buckling and to the first bar fracture. Additionally, points were also identified corresponding to the conventional column failure, i.e. for a strength reduction of 20% relatively to the maximum strength point, as adopted by Park and Ang [19]. In all tests, the observed cracks are predominantly horizontal, associated with the flexural dominant response of the studied columns. Clearly, biaxial loadings tend to induce more damage in the columns and, as expected, for these loading types the damage starts in the column corners. In the uniaxial tests damage can start also in the corners, but promptly spreads along the loaded sides of the column section. During the biaxial tests, the first bar fracture always corresponded to a section corner bar. The obtained results are presented in Figure 8b, showing that, with the biaxial load path, each damage state (cracking, yielding, etc.) occurs earlier, i.e. for lower drift levels, when compared with the uniaxial tests. As expected, the quadrangular load path is the most severe for the columns. Comparing the drifts associated with the damage states of buckling, conventional rupture and bar fracture, for the quadrangular and uniaxial tests, it was observed that the drift under biaxial loading is (*i*) 50% of the uniaxial drift value obtained for the stronger direction test and, (*ii*), 35% of that same drift when the test is made in the weaker direction. For the rhombus load path the drift for each damage state is about (*i*) 70% of the uniaxial test drift in the stronger direction and (*ii*) 50% in the weaker direction. The circular load path, tested only in the square section column, led to intermediate results between the experimental results for the rhombus and quadrangular loading paths. The cruciform load path applied in column N03 induced damage pattern and evolution very similar to that observed for the column uniaxially tested in its stronger direction. From the analysis of the damage evolution, it is clear that the conventional failure of the column occurs for drift levels close to the value corresponding to the reinforcing bar buckling.

3.4. Hysteresis dissipation energy

The cumulative hysteretic dissipation energy was calculated for all the cyclic tests performed, considering the shear-drift results in the X and Y direction, and the total energy was computed as the sum of the energy for both directions. The results in terms of evolution of cumulative dissipated energy are presented in Figure 8c. For each displacement amplitude level, the plotted value of dissipated energy corresponds to the end of the third cycle. Comparing the two uniaxial test results, as expected, lower energy dissipation was observed for the column tested in its weaker direction associated with the more reduced column strength in that direction. The biaxial load paths tend to induce larger amounts of dissipated energy, in particular for the quadrangular load path. In fact, this loading path imposes larger total lateral displacement for the load paths corners and, consequently, more damage is observed as reported in the previous section. Comparing load paths with the same total displacement amplitude (columns N03 and N04 or columns N14 and N16), the results in terms of dissipated energy evolution are similar (see Figure 8c). It was also interesting to observe that the sum of dissipated energy in the two unidirectional tests, X and Y directions, leads to an evolution of dissipated energy curve very close to that derived from the rhombus load path.

4. FINAL REMARKS

The main objective of this testing campaign focused on the study of RC columns behaviour subjected to cyclic horizontal uniaxial and biaxial loading paths provided by imposed lateral displacements combined with constant axial force. Sixteen column specimens were constructed and tested as cantilevers, for which the main variables considered were restricted to the lateral displacement paths and the column section geometry. The experimental results have shown the coupling effect between the two transversal directions that leads to lateral stiffness and strength decrease for the column in each principal direction, when compared with the corresponding values for uniaxial loading direction. The measured biaxial force paths are found rotated when compared with the horizontal displacement paths imposed in the tests, in accordance with previous findings reported by other authors. In this study it was concluded that the path rotation depends on the column geometry. In line with the stiffness and strength reduction in each transverse direction due the biaxial loading, the coupling effect between the column response in both directions leads to an increased hysteretic energy dissipation. The analysis of damage observed in all tests (cracking, concrete spalling, bar buckling and bar fracture) confirms that biaxial loading paths strongly influence the damage evolution. For quadrangular loading paths, conventional rupture was achieved for drift values corresponding to 50% of that observed for uniaxial tests.

Finally, it is worth emphasizing that many questions are still open in the field of biaxial behaviour of RC columns, especially these associated with the response dependency of the loading paths. Therefore more experimental research should be developed in this domain particularly considering that the cyclic tests performed within this work (by imposing smooth and regular displacement paths) may not be representative of the displacements actually imposed by earthquakes. Nevertheless, the research work herein briefly reported is expected to contribute for better understanding the biaxial response of RC columns and to provide an additional contribution for the calibration of suitable numerical models for the biaxial lateral response of reinforced concrete columns under cyclic reversals.

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